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EFFECTIVE RECOMBINATION COEFFICIENT
IN THE LOWER IONOSPHERE 5

by
G. Nesterov 9
[USSR]

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EFFECTIVE RECOMBINATION COEFFICIENT
IN THE LOWER IONOSPHERE *

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by G. Nesterov

SUMMARY

The total equation for the effective recombination coefficient α' in the lower ionosphere is analyzed. The expression is obtained for the determination of variations of the dissociative recombination coefficient as a function of temperature and of the zenithal angle of the Sun. It is shown that the temporal variations of the negative ion factor exert a substantial influence on the value of α' , particularly in the lower part of the D-region. The dissociative recombination is the determining factor for altitudes above the 80 - 85 km range.

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Because of increased interest in the lower ionosphere, a series of contributions have been lately made to the research on neutralization processes in the lower ionosphere, namely in the D-region and below the E-layer maximum. While a great number of data on the physical essence of microprocesses exist for altitudes of the atmosphere above 100 km, accessible for research by the method of vertical pulse sounding, there is still an insufficient amount of information on neutralization processes. The causes of such a delay must be sought for mainly in the great physical, methodological and technical difficulties with which the research work in the lower atmosphere is beset.

The full information on ionization-neutralization processes for heights exceeding 100 km is included in the reviews [1, 2]. Material on the lower ionosphere are dealt with in references [3 - 6] and others.

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Unfortunately, the discrepancies in the estimates of the recombination coefficient in the lower ionosphere reach one order and even more. The cause of this probably lies in the difference of ionospheric conditions during experiments and also in the difference of methods for determining the recombination coefficient. This leads to substantial difficulties when studying the physical nature, the behavior and the formation of the D-region during various solar -terrestrial conditions for a normal and disturbed ionosphere.

The effective recombination coefficient α' cannot be considered as a statistical quantity. Its value is determined by the quantitative correlation between the ionized gas component, the nature and the rate of physico-chemical and photochemical reactions taking place in the upper atmosphere, the local meteorological conditions in the considered region of the atmosphere and the zenithal angle of the Sun. Evidently, at such conditions α' will have an exactly determined value for every concrete case and the object of the present work is the analysis of causes conditioning the given value α' at a specific time, at the given place and for given conditions, and the uncovering of a method for its numerical determination and concrete representation of data on the value of α' . This research refers to middle geographic latitudes; however, the method may be applied under any conditions.

The effective recombination coefficient is a sum of three components

$$\alpha' = \alpha_d' + \lambda \alpha_i + \frac{1}{N(1+\lambda)} \frac{d\lambda}{dt}. \quad (1)$$

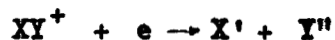
The first term accounts^{for} the effect of dissociative recombination, the second — that of ionic recombination and the third — the influence of negative ions' factor variation (λ) in the neutralization process. It is generally estimated that the latter is small and can be neglected by comparison with the first two together. For brevity we shall denote it by ϵ :

$$\epsilon = \frac{1}{N(1+\lambda)} \frac{d\lambda}{dt}, \quad (2)$$

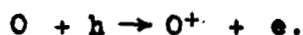
then (1) takes the form

$$\alpha' = \alpha_d' + \lambda \alpha_i + \epsilon. \quad (3)$$

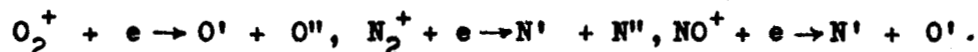
Let us now consider the behavior and the significance of each of the components (3). The dissociative recombination of the type



prevails in sectors with abundance of molecular ions XY^+ . On the other hand, positive molecular ions, for example those of oxygen (O_2^+), are created as a result of charge-exchange according to the reaction $O^+ + O_2 \rightarrow O_2^+ + O$, that is, in the region with sufficient concentration of atomic ions — in the case of O^+ . But, the atomic ions O^+ are the result of consecutive dissociation processes $O_2 + h \rightarrow O^+ + O$ and subsequent photoionization



Since the photodissociation of O_2 begins at a height greater than 80km, hence the dissociative recombination is the basic neutralization process in the thermosphere. Determinant above 80km are the dissociative recombination reactions of the type



It was established by numerous laboratory and ionospheric experiments that the coefficient of dissociative recombination of the i -th component of ion content varies with temperature T according to the law

$$\alpha_d^i = kT^{-n}, \quad (4)$$

at the same time the exponent n is different for various components of XY^+ . Bates and Dalgarno [7] find that α_d is proportional to $T^{-1/2}$, but other authors obtain for the exponent values from $-1/2$ to $2/3$. One of the last investigations [6] gives the following values of the specific dependence of α_d on T for various kinds of particles:

$$\alpha_d(O_2^+) = 7 \cdot 10^{-3} T^{-1} \text{ cm}^3 \text{ sec}^{-1}, \alpha_d(N_2^+) = 5 \cdot 10^{-3} T^{-1/2} \text{ cm}^3 \text{ sec}^{-1}, \\ \alpha_d(NO^+) = 1.5 \cdot 10^{-3} T^{-1/2} \text{ cm}^3 \text{ sec}^{-1}.$$

Ivanov-Kholodnyy [1, 2] proposes for atmospheric molecular ions O_2^+ , N_2^+ and NO^+ the dependence

$$\alpha_d = 5.2 \cdot 10^{-3} T^{-1/2} \text{ cm}^3 \text{ sec}^{-1} \quad (5)$$

basing himself mainly on ionospheric data.

From the investigations with mass-spectrometers installed on rockets it may be seen [8] that at solar culmination to heights ~ 100 km the ion O_2^+ is prevailing. A similar investigation [9] shows that, as the height of the Sun increases, the contribution of O_2^+ to the general ion content for heights ~ 100 km increases also. The ion NO^+ predominates above that level, and that is why the equivalent dissociative recombination coefficient for the $80 - 120$ km interval (α_d') is conditioned by the rate of vanishing of the component O_2^+ and NO^+ . For the n -components we may write

$$\begin{aligned}\frac{dN_1^+}{dt} &= q_1 + \alpha_1 N_1^+ N, \\ \frac{dN_2^+}{dt} &= q_2 + \alpha_2 N_2^+ N, \\ \frac{dN_n^+}{dt} &= q_n + \alpha_n N_n^+ N,\end{aligned}$$

whence, after summing up,

$$\begin{aligned}d(N_1^+ + N_2^+ + \dots + N_n^+) / dt &= q_1 + q_2 + \dots + q_n - \\ &- (\alpha_1 N_1^+ + \alpha_2 N_2^+ + \dots + \alpha_n N_n^+) N.\end{aligned}$$

Under quasi-equilibrium conditions we have

$$d(N_1^+ + N_2^+ + \dots + N_n^+) / dt = 0,$$

whence

$$N = \sum_i q_i / \sum_i \alpha_{d_i} N_i^+, \quad \sum_i q_i = N \sum_i \alpha_{d_i} N_i^+. \quad (6)$$

The general balance equation at $z > 80$ km in daytime has the form

$$dN / dt = q - \alpha_d' N^2,$$

But under quasi-equilibrium conditions $dN / dt \approx 0$, whence

$$q = \alpha_d' N^2. \quad (7)$$

But q and $\sum_i q_i$ are identical quantities, as a consequence of which we have from (6) and (7)

$$\alpha_d' = \frac{1}{N} \sum_i \alpha_{d_i} N_i^+. \quad (8)$$

Utilizing the average value of α_d for the i -th component, we obtain

$$\alpha_d' = \bar{\alpha}_{d_i} \left(\sum_i N_i^+ / N \right). \quad (9)$$

The expression (9) is identical to that obtained by another method in [10] for the formula of the effective recombination coefficient.

However, it is well known that while in daytime conditions the total concentration of positive ions is near the concentration of electrons, ($\lambda \ll 1$ at $z > 80$ km), in night time conditions the difference between them is significant ($\lambda \approx 1$ at $z = 100$ km). According to mass-spectrometric investigations [9], carried out on rockets in daytime and nighttime conditions, it has been established that the basic component O_2^+ varies from day to night according to the ratio $\sim 4 : 1$. From this conditions, as also from the well known law on temporal variations of electron concentration in the E-layer at $z \approx 100$ km, we may write on the basis of (9):

$$\alpha_d' = \bar{\alpha}_{d_1} (\cos \chi)^{-1/2}. \quad (10)$$

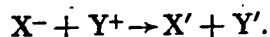
In accordance with the established temperature dependences for the dissociative recombination of the basic components at the heights considered by us, where $\alpha_d \sim T^{-1/2} \div T^{-3/2}$, we may assume $\alpha_d' \sim T^{-1}$ or $n = 1$. From absorption measurements in short waves in daytime ($\chi \approx 40^\circ$) we obtained for heights ~ 90 km the equivalent recombination coefficient $\alpha_{ae} \approx 2 \cdot 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ [11]. Under these conditions, and also from (4) and (10), we have

$$k = \alpha_d' T (\cos \chi)^{1/2}.$$

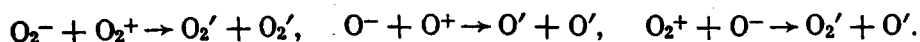
For the standard atmosphere CIRA-1961 (see [12]) $T = 181^\circ \text{ K}$ and $k = 3.47 \cdot 10^{-5} = \text{const.}$ Hence, we finally have for all zenithal angles up to $\chi = 100^\circ$:

$$\alpha_d' = 3.47 \cdot 10^{-5} / T (\cos \chi)^{1/2} \quad (11)$$

The second term of the equation (3) takes into account the influence of the ionic recombination, which responds to the reaction of the type



Since the negative nitrogen ions are unknown, the most important particles in that reaction remains the oxygen



Evidently, O_2 plays in the ionic recombination in the daytime D-region a role of first degree importance. Possible also are, however, the secondary reactions



The generally admitted value of α_i is $\alpha_i \approx 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$. There is an indication that as the temperature decreases, so does α_i , but the empirical dependences are unknown.

Let us examine the role of negative ions represented by the factor $\lambda = N^-/N$ and the rate of $d\lambda/dt$ variation with time. Here N^- and N are the densities of negative ions and electrons, respectively. Under daytime conditions the stationary value of λ is given by Nicolet in [13]

$$\lambda = \beta n / \gamma_1 + \gamma n, \quad (12)$$

where β is the adhesion factor of electrons to neutral atmospheric gas molecules of density n ; γ_1 is the photodetachment coefficient; γ is the collisional detachment coefficient. As already mentioned, the process of electron adhesion to N_2 and N is unknown and that is why n may be replaced in the numerator of (12) by $n(O_2)$. According to [14, 15],

$$\beta = \kappa n(O_2), \quad (13)$$

where $\kappa = (2 \pm 1) \cdot 10^{-30}$ at $T = 250^\circ \text{ K}$. On the other hand, γ_1 varies with $\cos \chi$ [16, 17]; at the same time from (12) we have

$$\lambda = \kappa n^2(O_2) / \gamma_{10} \cos \chi + \gamma n. \quad (14)$$

For the detachment coefficient γ_{10} of the ion O_2^- values from 0.035 to 0.44 sec^{-1} are given [18 - 21], and for the collisional detachment coefficient — the value $\gamma = 10^{-17}$ to $4 \cdot 10^{-20}$ depending upon the kind of particles and temperature [20, 22]. On the basis of the results presented in the equation (14), we assume $\gamma_{10} = 0.2 \text{ sec}^{-1}$ and $\gamma = 10^{-18} \text{ cm}^3 \text{ sec}^{-1}$. With these parameters and the data for $n(O_2)$ [23] we obtained for the standard atmosphere of [12] the family of curves $\lambda = f(z)$ $\chi = \text{const}$, represented in Fig. 1. It may be seen that during sunrise and sunset λ varies rapidly with time. We shall obtain the rate of λ variation with time by differentiating the equation (14)

$$\frac{d\lambda}{dt} = \frac{\partial \lambda}{\partial (\cos \chi)} \frac{\partial (\cos \chi)}{\partial h} \frac{\partial h}{\partial t}$$

whence, upon utilization of equations for χ and certain transformations, we shall obtain

$$\frac{d\lambda}{dt} = \lambda \frac{\gamma_{10} \cos \varphi \cos \delta \sin h}{\gamma_{10} \cos \chi + \gamma n} \frac{dh}{dt}. \quad (15)$$

Here φ, δ, h is the geographic latitude, the solar declination and the hour angle of the Sun, respectively. It is clear that λ is not a constant quantity, as usually assumed, and $d\lambda/dt$ has a specific value for each concrete case by time and place.

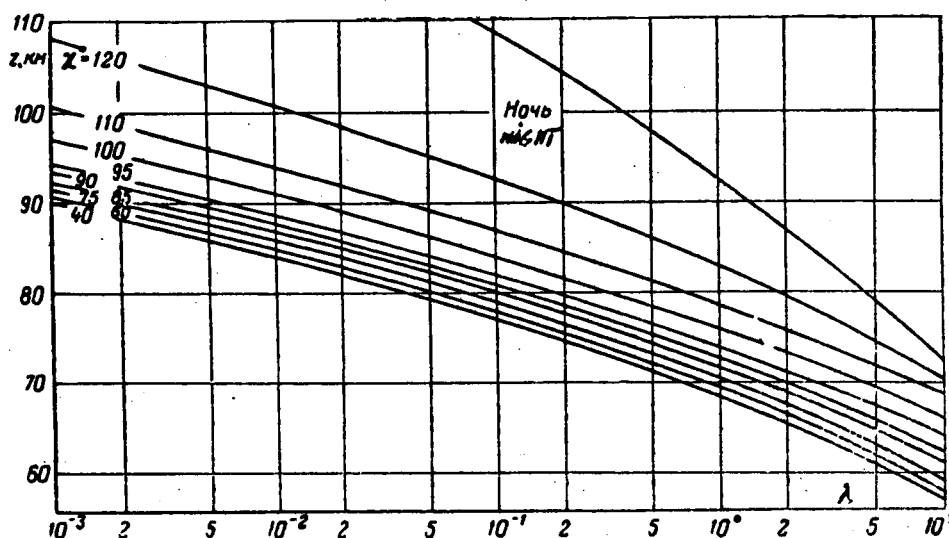


Fig. 1

Evidently, the function $\cos \chi$ in the equations (14), (15) can be substituted by $(\sec \chi)^{-1}$, and the latter, at zenithal angles $\chi \geq 75^\circ$ — by the Chapman function $f(\chi, z)^{-1}$. Under these conditions, the term ϵ in the equation (3) is plotted in Fig. 2 for mean geographical latitudes and equinoxes as a function of height z at parameter χ . At the same time, utilized for N are the quantities obtained by measurements of absorption in short and medium waves in the D-region and in various experiments with rockets, representing the partial reflection and the nonlinear effects in the lower ionosphere. Since the intense photodetachment of electrons from O_2^- begins at zenithal angles $\chi = 100^\circ$ [24, 25], χ was replaced by the equivalent angle $\chi' = \chi - 10^\circ$. The family of curves $\lambda\alpha_1(z)$ is also plotted in Fig. 2. It may be seen that in the $z = 70 \rightarrow 80$ km altitude interval the components ϵ and $\lambda\alpha_1$ are of the same order and that the admission, often encountered in literature, that ϵ is a very small quantity, is not justified. Here too are shown the groups of curves reflecting the contribution of the dissociative

recombination α'_d to the total neutralization process under conditions of standard atmosphere which were obtained from the equation (11). It may be seen that the dissociative recombination is determining for heights > 85 km in daytime and above 95 km at nighttime. For the sake of comparison we gave two curves for the profile of $\alpha'_d(z)$ (upper curve according to calculations of ref. [1, 2], lower curve — according to [6]). As may be seen, our curves are an acceptable compromise between these two results.

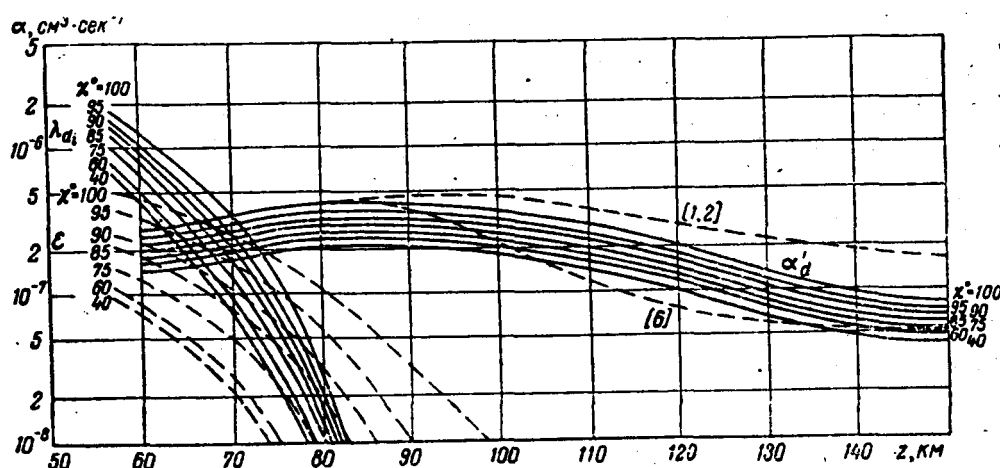


Fig. 2

The effective recombination coefficient, generalizing the result of the effect of these three components, is plotted in Fig. 3 after the equation (3); the parameter is the zenithal angle of the Sun χ . As already mentioned, for heights below 80 km, the ionic recombination and the variation of the factor of negative ions have a special value, while above that limit the dissociative recombination becomes determinant. The peculiar shape of the profile for $\alpha'(z)$ is evidently due to the temperature inversion in the region of the mesopause.

Let us recall that the given profile of $\alpha'(z)$ constitutes only one example responding to conditions on middle geographical latitudes for the periods of spring and autumn equinoxes, and it refers to average meteorological and aeronautical conditions in the upper mesosphere. With another setup $\alpha'(z)$ may undergo substantial deflections, depending upon the concrete conditions in the sector considered. In particular, α' will have a seasonal and latitude course — result of annual temperature variations and meridian

effect, and also of density fluctuations and neutral gas content. It is possible also that α' will undergo the well known variation with the period of solar activity.

It is interesting to compare the results obtained by us for the quantity α' with other well known literature data. To that effect we plotted in Fig. 4 the profiles of α' for $\chi = 40$ and 90° , computed by our methods and those obtained by other methods [1, 2, 4, 5, 6]. Circles denote the results of separate estimates of α' under different ionosphere conditions and for different measurements. At 115 km the value of α' was computed in [26] at time of the total solar eclipse of 15 February 1961. As was noted in [26] the value of α' obtained in that investigation is the smallest possible for the effective recombination in the E-layer : $\alpha' \geq 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ (arrow on the point in Fig. 4). The value of α' for $z = 90 \text{ km}$ was obtained in [11] on the basis of relaxation and equivalent electron density in the D-region. The value of α' at 77.5 km ($\alpha' = 5 \cdot 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$) constitutes the average according to measurements of [27] during experimental nuclear explosions in the upper atmosphere. According to investigations during chromospheric flares attended by X-ray emission, Nestorov and Taubenheim [28] have determined the mean effective recombination coefficient out of 400 ionospheric effects ($\alpha' \approx 1.3 \cdot 10^{-6} \text{ cm}^3 \text{ sec}^{-1}$) at an average altitude $z = 75 \text{ km}$, which is two to three times more than the value of α' at quiet ionosphere. It is interesting that other authors too obtained overrated values for α' at times of chromospheric flares. Thus, Swift [29] found the mean value of α' from absorption measurements with the aid of riometers (SCNA) to be $\alpha' \approx 6.7 \cdot 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ for $z = 80 \text{ km}$, while Mitra [30] obtained $\alpha' = 4 \cdot 10^{-6}$ for $z = 65 \text{ km}$ and Volland [31] hit higher values at $\alpha' = 9 \cdot 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ for $z = 70 \text{ km}$.

These comparatively high values of α' are possibly conditioned by high variation rates of the factor of negative ions ($d\lambda/dt$) during solar chromospheric flares. The value $\alpha' = 3 \cdot 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$, obtained in [32] for $z = 70 \text{ km}$, constitutes an exception.

The profiles of $\alpha'(z)$ for winter conditions and in the presence of a high temperature gradient in the region of the mesopause, obtained

by applying our own method to the data of temperature measurements by rockets [33] are given in Fig. 4.

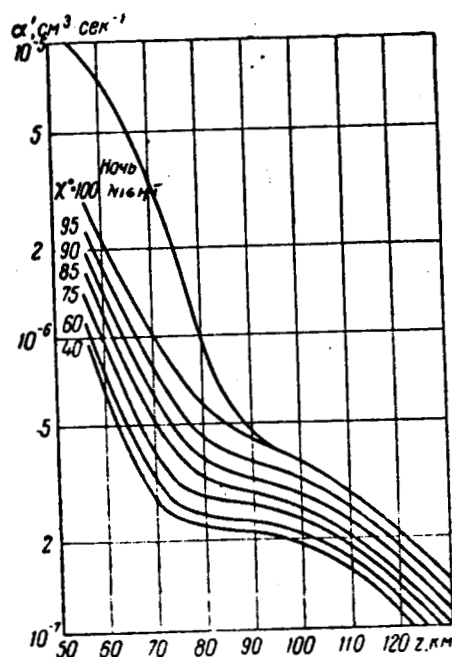


Fig. 3

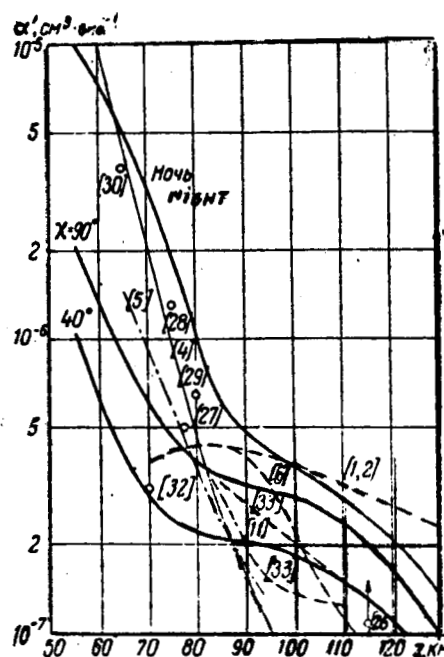


Fig. 4

A satisfactory agreement between the results obtained by us for the altitude range above 80km is clearly visible. Below 80km the data from reference [4] are strongly overrated, which apparently is the result of an overestimate of the role of the ionic recombination in the value of the effective recombination coefficient in the lower part of the D-region.

**** THE END ****

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References follow../..

REFERENCES

1. G. S. IVANOV-KHOLODNYI. Geomagn. i aeronomiya, 2, No. 3, 377, 1962.
2. G. S. IVANOV-KHOLODNYI. Geomagn. i aeronomiya, 2, No. 4, 674, 1962.
3. M. NICOLET, A. AIKIN. J. Geophys. Res., 65, 1464, 1960.
4. A. P. MITRA. J. Geophys. Res., 64, 733, 1959.
5. A. WAYNICK. The physics of the ionosphere. Phys. Soc. Conference, Cambridge, 1, 1954.
6. R. WHITTEN, I. POPPOFF. J. Atmos. Sci., 21, 117, 1964.
7. D. R. BEYTS, A. DALGARNO. Atomnyye i molekulyarnyye protsessy (pod red. D. Beytsa), IL, 1964.
8. C. Y. JONSON. J. Geophys. Res., 63, 443, 1958.
9. V. G. ISTOMIN. Sb. "Iskusstvennyye sputniki Zemli," No. 7, Izd-vo A. N. SSSR, 64, 1961.
10. A. D. DANILOV. Dokl. A. N. SSSR, 137, No. 5, 1098, 1961.
11. G. NESTOROV. Compt. rend. Acad. Bulg. Sci., 17, No. 12, 1091, 1964.
12. Space Research II Symposium COSPAR, Florence, 1961.
13. M. NIKOLE. Aeronomiya, IL, 1964.
14. L. M. CHANIN, A. V. PHELPS, M. A. BIONDI. Phys. Rev. Letters, 2, 344, 1959.
15. E. H. HOLT. Bull. Amer. Phys. Soc., 4, 112, 1959.
16. S. K. MITRA. The upper atmosphere. Calcutta, 1952.
17. K. SERAFIMOV. Izv. Geofiz. in-ta Bolgarsk. A. N., 5, No. 2, 69, 1964.
18. D. S. BURCH, S. J. SMITH, L. M. BRANSCOMB. Phys. Rev., 112, 171, 1958.
19. G. P. KNIPER. The Sun. Univ. of Chicago Press, 1953.
20. A. V. PHELPS, J. L. PACK. Phys. Rev. Letters, 6, 111, 1961.
21. R. C. WHITTEN, I. G. POPPOFF. J. Geophys. Res., 66, 219, 1961.
22. D. K. BAILEY, L. M. BRANSCOMB. Bull. Amer. Phys. Soc., 5, 123, 1960.
23. H. FRIEDMAN, T. A. CHUBB, J. M. SIOMKAJLO. IQSY, Instrum. Manual, No. 9
89, 1964.

24. G. NESTOROV. Compt. rend. Acad. Bulg. Sci., 15, No. 4, 373, 1962.
25. G. NESTOROV. Izv. Geofiz. in-ta Bolgarsk. A. N. 3, 243, 1962.
26. G. NESTOROV, J. TAUBENHEIM. J. Atmos. and Terr. Phys., 24, 633, 1962.
27. R. E. LE LEVIER. J. Geophys. Res., 69, 481, 1964.
28. G. NESTOROV, I. TAUBENKHEYM. Izv. Geofiz. in-ta Bolgarsk. A. N., 7, 1965
(v pechatl).
29. D. W. SWIFT. J. Atmos. and Terr. Phys., 23, 29, 1961.
30. S. N. MITRA. J. Atmos. and Terr. Phys., 26, 375, 1965.
31. H. VOLLAND. J. Atmos. and Terr. Phys., 26, 695, 1964.
32. G. ENIZIAN. Ber. Geophys. Symposium. Sofia, 1964.
33. N. W. SPENCER, R. L. BOGGESS, D. R. TAEUSCH. J. Geophys. Res., 69, 1367, 1964.

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